

# **Discrete Scattering in Marine Sediments**

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## **LONG-TERM GOALS**

The goal of this research is to better understand the physics and mechanisms of sound-seabed interaction, including acoustic penetration, propagation, attenuation and scattering in marine sediments.

## **OBJECTIVES**

The scientific objective of this research is to develop analytical and numerical approaches to describe and quantify acoustic scattering from rough heterogeneous sea beds with discrete inclusions.

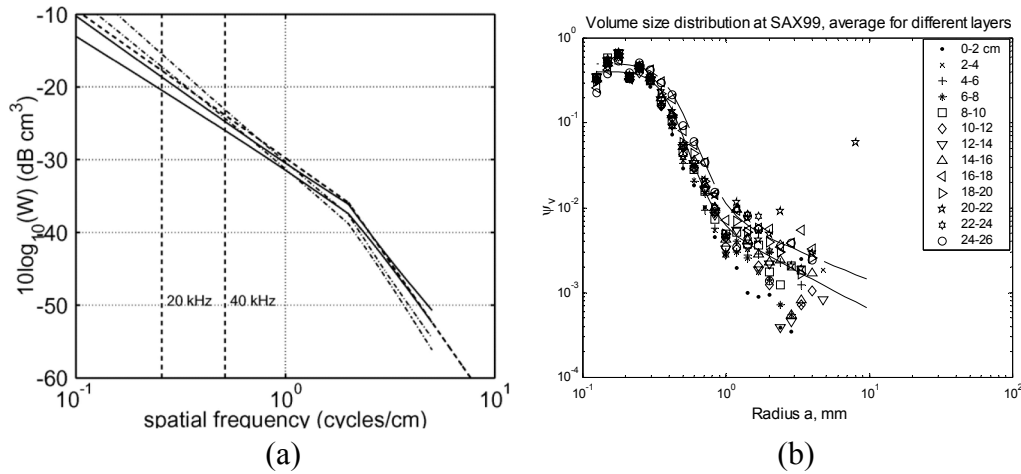
## **APPROACH**

Testing various models and mechanisms of high frequency seabed scattering was one of primary goals of recent major experiments in sediment acoustics, SAX99 and SAX04, conducted near Ft. Walton Beach, Florida [1-4]. The models to test were based on various assumptions about dominance of certain scattering mechanisms and corresponding theories of scattering. Such models, confirmed by experiments, would provide necessary relationships between seabed parameters related to those mechanisms and characteristics of the scattered field. The relationships themselves are required for solution of practical problems such as prediction of bottom reverberation given seabed properties or/and inversion of various seabed parameters from acoustic scattering data.

There are different mechanisms of seabed scattering which are due to different types of seabed medium irregularities: continuous volume fluctuations of the sediment acoustic parameters and discrete volume inclusions (rock, shell hash, etc.), roughness of the seabed interfaces, as well as volume-roughness interactions. In the case of a continuous medium, the bottom scattering strength can be expressed in terms of the spatial spectra of inhomogeneity (spatial fluctuations of acoustical parameters) and the interface roughness spectra [5]. In the case of discrete inclusions, the scattering strength can be expressed through the individual scattering functions of the targets and statistical distributions of their parameters (size, shape, orientation, material, etc) [6]. The distributions themselves can be spatially non-uniform, for example, depth-dependent (stratified) [7,8], which is usual for the ocean environment. In this research, an approach using an incoherent summation of scattered intensities from discrete targets was used to obtain the expressions for the bottom scattering strength [6-8].

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Extensive measurements of roughness spectra and other sediment parameters at SAX99 allow, using various models of roughness scattering, prediction of the seabed roughness scattering strength and comparisons with observed bottom scattering at different frequencies and grazing angles [3]. As to volume scattering, analysis and model/data comparisons for SAX99 have showed that contribution of continuous volume fluctuations to total scattering at SAX99 site is much lower than that of roughness and, therefore, can be neglected [3]. The importance of another component of volume heterogeneity, which is due to discrete inclusions in the sediment, by the beginning of this project, had not yet been evaluated. In this research, an approach was to be developed to consider the role of discrete inclusions in the sediment. This would allow complete comparisons of volume and roughness scattering based on SAX99 environmental data, particularly, including the bottom roughness spectra and the sediment grain size-depth distributions presented in Figure 1.



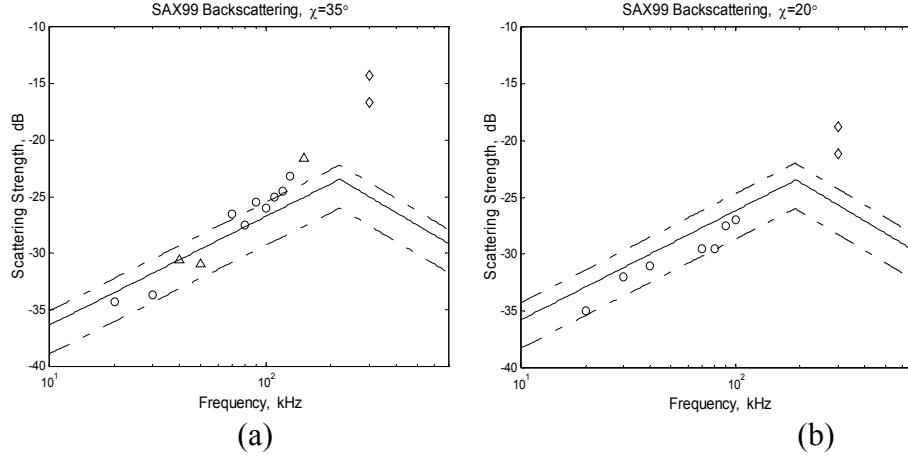
**Figure 1. Seabed surface roughness spectra (a) and sediment grain size-depth distribution (b) measured at the SAX99 site and used in bottom backscattering model/data comparisons.**

In Figure 1a, the roughness spectra at SAX99 are presented, which are well described by the bi-power law (shown by a number of regression lines) with a remarkable break at about 2 cycles/cm. In Figure 1b, the sediment grain size-depth distributions are shown. Different symbols represent averages within different layers of 2 cm thickness from the cores containing the top 26 cm of the sediment. It is seen that shape of the size distribution is quite different for different depths and different size intervals. For example, concentration of coarse fractions (gravel and shell) is low near the surface at 0-2 cm depth, while there is a remarkable shell layer at 20-22 cm depth. The solid line shows the best multi-power law fit to the data [6]. The slightly shifted dashed line will be used in model/data comparison below.

## WORK COMPLETED

Analysis of roughness scattering model/data comparisons was a starting point of this research. The results are illustrated in Figure 2, where various symbols show frequency dependence of bottom backscattering strength at two fixed grazing angles, 35 and 20 degrees, representing angles above (a) and below (b) the critical grazing angle, which is about 30 degrees for sandy sediments at the SAX99 site. Solid and dash-dot curves show roughness scattering prediction and bounds of uncertainty correspondingly. The comparison shows, within an allowed uncertainty, that the roughness scattering model fits the data reasonably well at frequencies below 100 kHz. However, at higher frequencies,

predicted roughness scattering is substantially lower than the observed level of scattering because the level of roughness spatial spectrum was found to be too low at the corresponding spatial frequencies at SAX99 site due to the above-mentioned break in the bi-power law [3]. Recent analysis [7] supports the existence of such an important break by showing its relationship to the angle of repose, a fundamental feature of granular sediments (such as sands). Therefore, analysis of roughness scattering model/data comparisons has shown that other mechanisms of scattering must be considered and other approaches are required for understanding SAX99 data.



**Figure 2: SAX99 roughness scattering model/data comparison: Frequency dependence of the bottom backscattering strength at a fixed grazing angle above (a) and below (b) critical.**

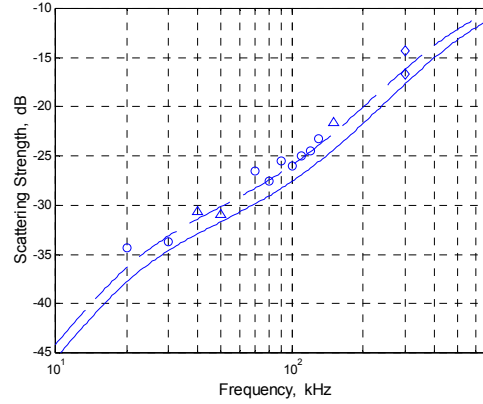
In this research, the discrete scattering mechanism was incorporated into analysis of SAX99 scattering data. An approach has been developed which allows description and quantification of the effects of the sediment discrete heterogeneity on bottom backscattering and comparison with roughness scattering mechanism in a wide frequency range of tens- to hundreds of kHz using the environmental data set obtained at the SAX99 site.

## RESULTS

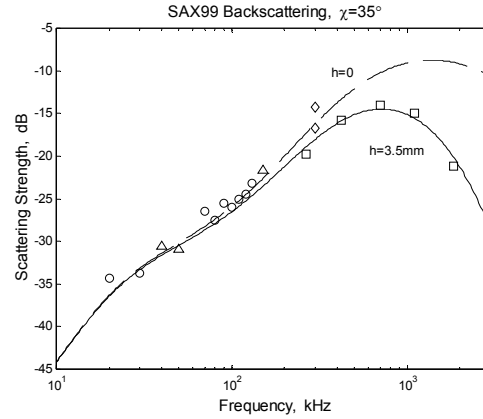
The first result was obtained using a simple version of the discrete scattering model which considers a statistically uniform depth-independent distribution of scatterers. This model was used in a discrete scattering model/data comparison [6]. The results of this comparison are shown in Figure 3. The backscattering data are the same as in Figure 2a for a fixed grazing angle, 35 degrees. The grain size distribution was taken as shown in Figure 1b by solid and dashed curves. Acoustic parameters of the sediment, the density and sound speed and attenuation, correspond to environmental measurements at the SAX99 site [1]. It is seen that such a simple model fits the data well at all the frequencies.

Next, this model was modified [7,8] to take into account the fact that the concentration of shell hash is low near the surface at 0-2 cm depth (see Figure 1b). This led to consideration of a thin (3.5 mm) top homogeneous (transition) layer placed on a sediment half-space with depth independent size distribution, which is taken here the same as shown in Figure 1b by the dashed curve. The results are presented in Figure 4 showing that the model provides both qualitative and quantitative explanation of some interesting experimental results obtained at the SAX99 site for higher frequencies (265-1850 kHz), including backscattering data roll-off above 1000 kHz, which has not been explained adequately

[9]. The result is shown in Figure 4 by the solid curve. The dashed line corresponds to the case without the transition layer and agrees well with data below 300 kHz but fails at higher frequencies.

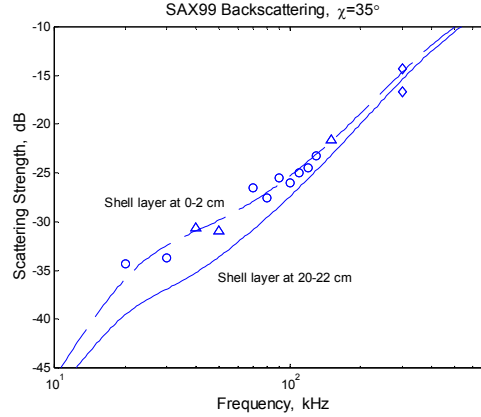


**Figure 3: SAX99 discrete scattering model/data comparison: Frequency dependence of the bottom backscattering strength. The grazing angle is 35 degrees. Solid and dashed curves correspond to a multi-power law for the scatterers size distribution shown in Figure 1b by solid and dashed lines respectively.**



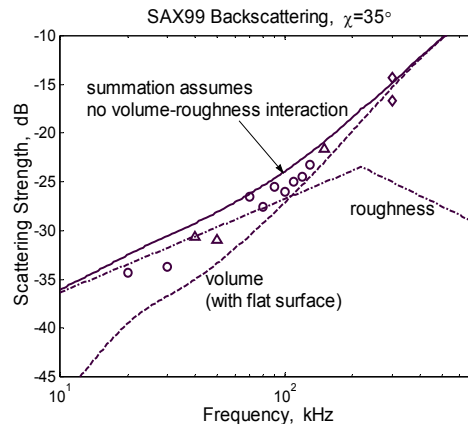
**Figure 4. Effect of a thin (3.5 mm) top homogeneous (transition) layer at high frequencies. The frequency dependence of the bottom backscattering strength at SAX99 shows a remarkable roll-off above 1000 kHz. The solid and dashed lines show results for a model of discrete scattering respectively with and without the transition layer.**

The most recent model [8] considers an arbitrary stratification of discrete inclusions, i.e., allows depth-dependent grain size distribution exactly corresponding to that measured at the SAX99 site [1]. The results for the frequency dependence of bottom backscattering strength are shown in Figure 5 by the solid line. Model/data comparison shows that the prediction of volume scattering using the measured size distribution is a few dB lower than the observed bottom scattering at SAX99 at frequencies below about 100 kHz. However, analysis shows that this discrepancy can be easily compensated. For this, one needs to assume that the shell layer is located near the sediment surface instead of its real location at about 20 cm depth. This possibility is illustrated by the dashed line which gives a good fit to the data.



**Figure 5. Effect of the shell layer location on frequency dependence of the bottom backscattering strength at SAX99 at a fixed grazing angle (35 degrees). The shell layer is placed at the 20-22 cm depth (solid line) and 0-2 cm depth (dashed) respectively.**

Nevertheless, the more adequate way to fulfill this discrepancy is to remember the contribution of roughness scattering (see Figure 2a). It is easy to see that a simple summation of the two mechanisms, roughness and discrete volume scatterers, provides a good model/data comparison for backscattering for all frequencies used in SAX99 at grazing angles above critical. This result is illustrated in Figure 6.

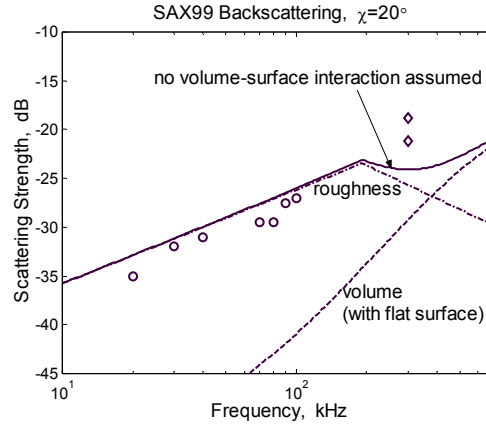


**Figure 6: Model-data comparison for frequency dependence of SAX99 seabed backscattering strength at a fixed grazing angle above critical. The model assumes a simple summation of the roughness and volume scattering components (no volume-roughness interaction).**

In a sense, this illustrates the physically understandable idea that the roughness of the water-sediment interface and a strongly scattering shell layer near the interface can be acting in a similar way, which can cause an ambiguity in interpretation of bottom scattering data. It also shows that the SAX99 environmental data set is complete in the sense that it allows resolution of this ambiguity by providing enough data for both bottom roughness spectra and sediment grain size-depth distributions.

Generally, the main accomplishment of this research by now is the development of a consistent model of bottom scattering for all frequencies used at SAX99 and for grazing angles above critical including

both volume and roughness components based on both acoustical and environmental SAX99 data. However, there is still a serious problem in understanding and modeling of backscattering for SAX99 at high frequencies (about 200 kHz and higher) at sub-critical grazing angles. This is demonstrated in Figure 7. Analogously to the case of grazing angles above critical, a simple summation of volume and roughness scattering was applied assuming no interaction between these two mechanisms. This means, that roughness scattering is being calculated for homogeneous sediment (with no inclusions) and discrete scattering is being considered assuming a flat sediment surface (no roughness). This simplified approach, used successfully at higher grazing angles, as demonstrated in Figure 6, fails in attempts to explain high frequency data at sub-critical grazing angles (see Figure 7).



**Figure 7: Model-data comparison for frequency dependence of SAX99 seabed backscattering strength at a fixed grazing angle below critical. The significant discrepancy at high frequencies may be due to ignoring volume-roughness interactions, which can enhance penetration and the volume scattering in the sediment.**

The discrepancy can be due to ignoring volume-roughness interaction. In the case of a flat water-sediment interface, at grazing angles below critical, volume scattering is significantly reduced because of the small depth of sound penetration into the sediment. In the case of a randomly rough interface, there are always facets with local grazing angles above critical, which cause an enhancement of sound penetration and consequent enhancement of volume scattering in the sediment [10]. The effect can be very significant considering the fact that the slope of roughness at sub-cm scales at SAX99--SAX04 site is large and can be close to both angle of repose and critical angle (about 30 degrees).

Therefore, results of this research show, in particular, that the contribution of gravel and shell inclusions and coarse sand fraction in total scattering at the SAX99 site can be dominating (over roughness) at high frequencies (about 100 kHz and higher) and grazing angles above critical (about 30 degrees) while roughness is likely a dominating mechanism of bottom scattering at lower frequencies and grazing angles below critical. A simple summation of the two mechanisms, roughness and discrete volume scatterers, provides a good model/data comparison for backscattering for all frequencies used in SAX99 at grazing angles above critical.

A problem remains at sub-critical grazing angles for high frequencies (about 200 kHz and higher) where there is a significant model/data discrepancy which can be due to ignoring volume-roughness interaction. The effects of such interactions can be very significant and require further theoretical

considerations and other approaches. One such approach, a unified approach to volume and roughness scattering [11], can be used to describe volume-roughness interactions in the sediments. It is exactly consistent with the small perturbation method, but it is not restricted by the smallness requirement for roughness height and slope, which makes it very appropriate tool for considering effects of non-small-slope roughness at SAX99-SAX04 conditions.

## **IMPACT/APPLICATIONS**

The models of seabed scattering developed in this research will provide a better understanding of bottom acoustic interaction at mid- and high-frequencies. In particular, they are proposed as basic components in follow-on research of bottom scattering including volume-roughness interactions.

## **TRANSITIONS**

The results of this work are being adapted in practical analysis of seabed scattering. For example, the model of discrete scattering developed in this research was proposed for using in SAX04 data analysis (ONR, Code 321OA). The original ideas and equations developed in this project, particularly, relationships between seabed properties and the bottom backscattering strength are proposed for using in improved algorithms for remote geoacoustic characterization of marine sediments (ONR, Code 321CG) and for updates of bottom reverberation codes (ONR, Code 321MS).

## **RELATED PROJECTS**

This project is closely connected to SAX04 program to strengthen its modeling component. This work was conducted in collaboration with investigators at the Applied Physics Laboratory, University of Washington (Drs. D. Jackson, K. Williams, D. Tang, E. Thorsos and others) and NRL (Drs. M. Richardson and K. Briggs).

## **REFERENCES**

1. M.D. Richardson et al, Overview of SAX99: Environmental Considerations, *J.Oceanic Engr.*, **26**, 26-53 (2001).
2. E.I. Thorsos et al, Overview of SAX99: Acoustic Measurements, *J.Oceanic Engr.*, **26**, 4-25 (2001).
3. K.L. Williams et al, Acoustic Backscattering Experiments in a Well Characterized Sand Sediment: Data/Model Comparisons Using Sediment Fluid and Biot Models, *J.Oceanic Engr.*, **27**, 376-387 (2002).
4. E.I. Thorsos et al, SAX04 overview, in, Boundary Influences in High Frequency Shallow Water Acoustics, N.G. Pace and P. Blondel (Eds), University of Bath, UK, pp.3-12 (2005).
5. A.N. Ivakin, Models of scattering for remote acoustic sensing of the seafloor, *Proc.Inst.Acoust.*, **23**: Part 2, 268-275 (2001).
6. A.N. Ivakin, Scattering from discrete inclusions in marine sediments, in *Proc. Seventh Europ. Conf. Underwater Acous., ECUA2004*, vol.1, 625-630 (Delft, The Netherlands, 2004).



7. Ivakin A.N. (2004), "Mechanisms of Scattering at SAX99 and SAX04: Roughness vs Discrete Scattering " (invited lecture), in, *Sediment Acoustics Experiment 2004 (SAX04) Workshop*, Seattle, Washington, 16-17 March 2004.
8. Ivakin A.N., "High frequency scattering from sandy sediments: roughness vs discrete inclusions", in, *Boundary Influences in High Frequency Shallow Water Acoustics*, N.G. Pace and P. Blondel (Eds), University of Bath, UK, pp.185-192 (2005).
9. Greenlaw C.F., D.V. Holliday and D.E. McGehee, High-frequency scattering from saturated sand sediments, *J. Acoust. Soc. Am.*, **115**, 2818-2823 (2004).
10. Ivakin A.N. and Yu.P. Lysanov, Underwater sound scattering by volume inhomogeneities of a bottom medium bounded by a rough surface, *Sov.Phys.Acoust.*, **27**, 212-215 (1981).
11. A.N. Ivakin, A unified approach to volume and roughness scattering, *J.Acoust.Soc.Am.*, **103**, 827-837 (1998).

## PUBLICATIONS

1. Ivakin A.N. (2005), "High frequency scattering from sandy sediments: roughness vs discrete inclusions", in, *Boundary Influences in High Frequency Shallow Water Acoustics*, N.G. Pace and P. Blondel (Eds), University of Bath, UK, pp.185-192.
2. Ivakin A.N. (2004), "Scattering from discrete inclusions in marine sediments", in, *Proc. Seventh European Conference on Underwater Acoustics (ECUA2004)*, Delft, The Netherlands, 5-8 July 2004, v.1, pp.625-630.
3. Ivakin A.N. (2004), "Mechanisms of Scattering at SAX99 and SAX04: Roughness vs Discrete Scattering " (invited lecture), in, *Sediment Acoustics Experiment 2004 (SAX04) Workshop*, Seattle, Washington, 16-17 March 2004.
4. Ivakin A.N. and Jackson D.R. (2004), "Near-Bottom Bistatic Measurements Technique for Acoustic Classification of the Sediment and Buried Objects", in, *Proc. The Application of Recent Advances in Underwater Detection and Survey Techniques to Underwater Archeology*, Bodrum, Turkey, 3-7 May 2004, pp.183-190.
5. Ivakin A.N., J.-P. Sessarego and P. Sanchez, (2005), "Laboratory study of high frequency scattering from water-saturated sandy sediments", *J. Acoust. Soc. Amer.*, **117**(4), Pt.2, p.2433.
6. Ivakin A.N. (2004), "Mechanisms of seafloor scattering: Roughness vs discrete inclusions " (invited), *J. Acoust. Soc. Amer.*, **116**(4), Pt.2, p.22575.
7. Ivakin A.N., Jackson D.R. and Tang D., (2003), "Separating volume and roughness components of scattering using spatial coherence filtering", *J. Acoust. Soc. Amer.*, **114**(4), Pt.2, p.2301-2302.

8. Ivakin A.N. (2003), "Models of discrete scattering in marine sediments", J. Acoust. Soc. Amer., **113**(4), Pt.2, p.2320.
9. Jackson D.R., Williams K.L., Ivakin A.N. and Thorsos E.I., (2003), "Use of a buried array to characterize sediment volume scattering", J. Acoust. Soc. Amer., **113**(4), Pt.2, p.2318.